Optical excitation of single- and multimode magnetization precession in Galfenol nanolayers

A. V. Scherbakov,[1,2] A. P. Danilov,[1] F. Godejohann[1], T. L. Linnik,[3] B. A. Glavin,[3] L. A. Shelukhin,[2] A. W. Rushforth,[4] D. P. Pattnaik,[4] M. Wang ,[4] D. R. Yakovlev,[1,2] A. V. Akimov,[4] and M. Bayer [1,2]

[1]*Experimentelle Physik 2, Technische Universität Dortmund, D-44227 Dortmund, Germany*
[2]*Ioffe Institute, 194021 St. Petersburg, Russia*
[3]*Department of Theoretical Physics, V.E. Lashkaryov Institute of Semiconductor Physics, 03028 Kyiv, Ukraine*
[4]*School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, UK*

SUPPLEMENTAL MATERIAL

1. Dispersion of the magnon modes and azimuthal dependence of the ground mode frequency in the 120-nm $Fe_{0.81}Ga_{0.19}$ layer.

If the exchange field is considered, the magnetization precession frequency f is determined by the standard expression [1,2]:

$$f = \frac{\gamma_0}{2\pi}\sqrt{F_{\varphi\varphi}\cdot F_{\theta\theta} + (F_{\varphi\varphi} + F_{\theta\theta})Dq^2 + D^2q^4}\,. \tag{S1}$$

Here γ_0 is the gyromagnetic ratio, D is the exchange spin stiffness coefficient, q is the spin wave wavevector, and $F_{\theta\theta} = \frac{\partial^2 F_M}{\partial\theta^2}$ and $F_{\varphi\varphi} = \frac{\partial^2 F_M}{\partial\varphi^2}$ are the second derivatives of the free energy density on the azimuthal angle, φ, and polar angle, θ, calculated at the equilibrium orientation of magnetization: $\varphi=\varphi_0$ and $\theta=\theta_0=\pi/2$ (for the used experimental geometry). With the free energy density in the form used in Ref. [3] assuming of zero strain we get:

$$\begin{aligned} F_{\theta\theta} &= \frac{K_1}{2}(\cos 4\varphi_0 + 3) + 2B_d + K_u\cos\left(\varphi_0 - \frac{\pi}{4}\right) + B\cos(\varphi_0 - \varphi_B), \\ F_{\varphi\varphi} &= 2K_1\cos 4\varphi_0 + K_u\cos\left(\varphi_0 - \frac{\pi}{4}\right) + B\cos(\varphi_0 - \varphi_B), \end{aligned} \tag{S2}$$

where K_1 and K_u are the cubic and uniaxial anisotropy coefficients, respectively, and $B_d = \mu_o M_0/2$ is the demagnetizing field (M_0 is the saturation magnetization). In the case of strong magnetic fields and/or small spin wave vectors Eq. (S1) can be simplified to:

$$f \approx f_0 + \frac{\gamma_0}{2\pi}\beta Dq^2, \tag{S3}$$

where $f_0 = \gamma_0/(2\pi)\cdot\sqrt{F_{\varphi\varphi}F_{\theta\theta}}$ is the ground mode frequency and $\beta = (F_{\varphi\varphi} + F_{\theta\theta})/2\sqrt{F_{\varphi\varphi}F_{\theta\theta}}$ is the field-dependent coefficient, which approaches 1 with the increase of B.

Due to the large number of the fitting parameters (K_1, K_u, M_0, D) they cannot be obtained with high accuracy only from the magnon mode dispersion shown in Fig. 1(c) in the main text. For a better fitting procedure, we have measured the azimuthal dependence of the ground magnon mode frequency in the 120-nm $Fe_{0.81}Ga_{0.19}$ layer. The measured $f_0(\varphi_B)$ at B=200 mT is shown by symbols in Fig. S1. The measurements were carried out at room temperature at the ASOPS-based setup. The best

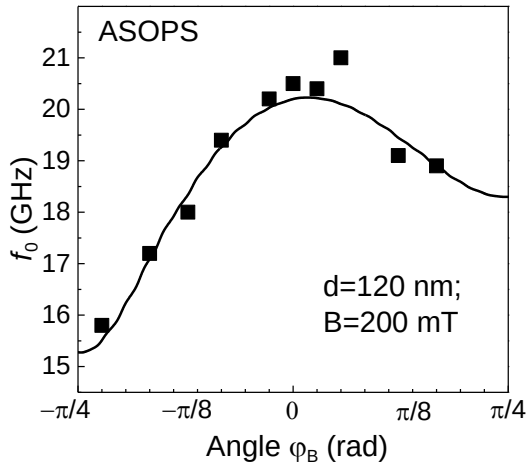

Figure S1.
Angular dependence of the precession frequency of the ground magnon mode in the 120-nm $Fe_{0.81}Ga_{0.19}$ layer. Symbols show the experimental data; solid line is the calculated dependence for the chosen anisotropy parameters.

agreement between the calculated and experimental dependences $f_0(\varphi_B)$ (Fig. S1) and $f_n(n)$ [Fig 1(c) in the main text] has been achieved with the assumption of pinning boundary conditions and the following anisotropy parameters: K_1=18 mT, K_u=15 mT, $\mu_0 M_0$=1.85 T, D=1.5×10^{-17} Tm^2, which are in good agreement with the previously reported values [3,4].

2. Azimuthal dependence of the main precession parameters in the 4-nm $Fe_{0.81}Ga_{0.19}$ layer.

We performed also a comprehensive study of the 4-nm $Fe_{0.81}Ga_{0.19}$ layer to obtain its anisotropy parameters. Figure S2 summarizes the experimental and calculated angular dependences of the precession frequency, f, amplitude, A, and damping parameter, a_{eff}, for the external magnetic field B=200 mT. The measurements were carried out also at room temperature at the setup equipped with the ASOPS system. The anisotropy parameters for this layer are: K_1=15 mT, K_u=5 mT, $\mu_0 M_0$=1.72 T. Comparing heating in the 4-nm layer and thick galfenol films from Ref. [3], we estimated for our case the changes of cubic and uniaxial anisotropy coefficients under the femtosecond optical excitation as $\Delta K_{1.}$ = - 3.7 mT and ΔK_u= -0.8 mT.

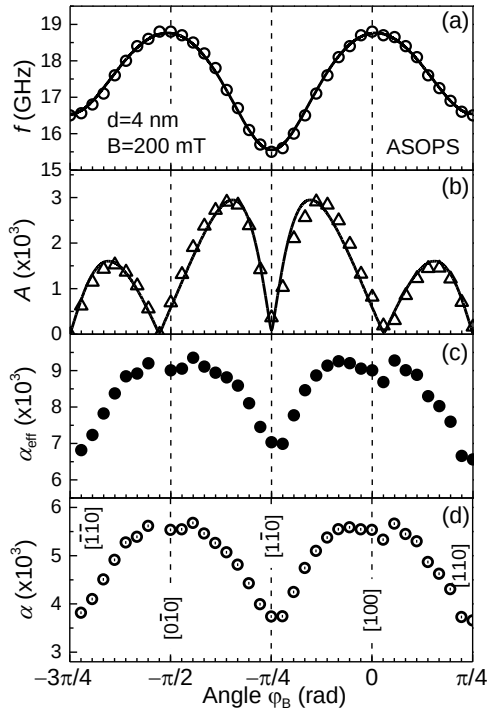

Figure S2.
Azimuthal dependences of the precession frequency (a), amplitude (b), damping parameter α_{eff} (c) and Gilbert damping α (d) in the 4-nm $Fe_{0.81}Ga_{0.19}$ layer. Symbols show the experimental data; solid lines are the calculated dependences.

We also calculated the azimuthal dependence of the Gilbert damping coefficient α from the experimental values of α_{eff} to check the damping anisotropy in the studied structure. For this procedure, we used the standard expression for relaxation time, τ, of the magnetization precession [1], which gives the following expression for the experimentally measured α_{eff}:

$$\alpha_{eff} = \frac{1}{2\pi f \tau} = \frac{\alpha \gamma_0}{4\pi f}\left(F_{\theta\theta} + F_{\varphi\varphi}\right). \quad \text{(S4)}$$

The obtained dependence $\alpha(\varphi_B)$ at B=200 mT is shown in Fig. S2(d). As one can see there is a pronounced dependence of α on the direction of the external magnetic field. This dependence is in good agreement with the previously reported anisotropy of Gilbert damping in Fe films on GaAs [5].

3. Demagnetization of the 4-nm $Fe_{0.81}Ga_{0.19}$ layer under femtosecond optical excitation.

We measured the changes of the saturation magnetization of the 4-nm layer under femtosecond laser impact. We monitored the time evolution of the longitudinal Kerr rotation induced by pump pulses of 1030 nm wavelength with 10-kHz repetition rate, which was low enough for complete recovery of the studied layer to equilibrium conditions. The probe beam of the same wavelength was incident at 45° to the surface plane. Figure S3 shows the demagnetization traces measured for the pump excitation density varied between 4 and 24 mJ/cm^2. At the density of 1 mJ/cm^2 used in the main experiments on the excitation of magnetization precession, the demagnetization effect should be insignificant. One can see from the figure that the demagnetization occurs on the time scale from sub- to several picoseconds depending on the excitation density.

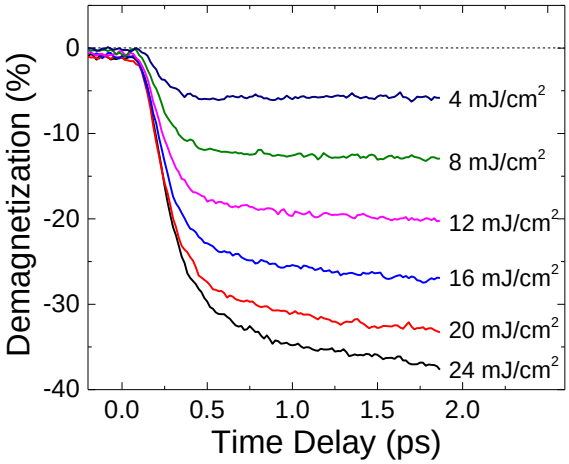

Figure S3.
Ultrafast demagnetization of the 4-nm $Fe_{0.81}Ga_{0.19}$ layer induced by the femtosecond optical excitation of respective density at B=10 mT applied at φ_B=0.

References.

[1] A.G. Gurevich, G.A.Melkov, Magnetization Oscillations and Waves (CRC-Press, Boca Raton, 1996)

[2] S. Shihab, H. Riahi, L. Thevenard, H.J.von Bardeleben, A.Lemaitre, and C. Gourdon, Appl. Phys. Lett. **106**, 142408 (2015).

[3] V. N. Kats, T. L. Linnik, A. S. Salasyuk, A. W. Rushforth, M. Wang, P. Wadley, A. V. Akimov, S. A. Cavill, V. Holy, A. M. Kalashnikova, and A. V. Scherbakov, Phys. Rev. B **93**, 214422 (2016).

[4] D. B. Gopman, V. Sampath, H. Ahmad, S. Bandyopadhyay, and J. Atulasimha, IEEE Trans Magn. **53**, 6101304 (2017).

[5] Y. Zhai, C. Ni, Y. Xu, Y. B. Xu, J. Wu, H. X. Lu, and H. R. Zhai, J. Appl. Phys. **101**, 09D120 (2007).